Reduction of tantala mechanical losses in Ta_2O_5/SiO_2 coatings for the next generation of VIRGO and LIGO interferometric gravitational waves detectors

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Abstract

Mirror thermal noise in Ta_2O_5/SiO_2 coatings is predicted to be the limiting noise in the 50-300 Hz frequency range in the interferometric gravitational wave detectors. Ta_2O_5 losses were dominating compared to the SiO_2 losses. We developed a model to calculate multilayer mechanical losses and we are working for low mechanical losses Ta_2O_5/SiO_2 coatings.

Keywords: Gravitational waves; thermal noise; mechanical losses

1. Introduction

Mirror thermal noise is the main source of perturbation of measurements in the 50-300Hz frequency range for current interferometric gravitational wave detectors as shown in figure 1. Next generations of VIRGO and LIGO optics will have to improve the sensitivity of the detectors in this frequency range. Thermal noise[i] is given by

$$S_X(f) = \frac{2k_B T \; W_{diss}}{\pi^2 f^2 \, F_0^{\,2}} \tag{1}$$

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where k_B and T are Boltzmann's constant and the temperature of the mirror, F_0 is the amplitude of the oscillation and W_{diss} the power dissipated in the test mass. The thermal noise is caused by mechanical losses in the system according to the Fluctuation-Dissipation Theorem[ii]. Mechanical losses in coatings (multilayers of dielectric materials alternating SiO_2 and Ta_2O_5) are the main source of dissipation. Several losses occur in the expression of the mechanical losses as clamping losses, thermo elastic losses, bulk losses, gas losses, surface losses and others loss[iii].It was already proved that the Ta_2O_5 losses were dominating compared to the SiO_2 losses. Actually there is a ratio six between the SiO_2 losses and the Ta_2O_5 losses:

$Ø_{Ta2O5}$=3.02.10^{-4} +/- 0.11. 10^{-4}

$Ø_{SiO2}$=0.5.10^{-4} +/- 0.018. 10^{-4}

We actually work on the improvement of the mechanical properties of the coating materials and we developed a measurement bench in collaboration with INFN Perugia. With this bench we measure the mechanical quality factor ($Q=\pi f_0 \tau$, where f_0 is the frequency resonance and τ is the decay time) of materials for different frequencies modes and consequently their mechanical losses ($Ø_{(f0)}=1/Q$).

We also developed an analytical model to calculate the mechanical losses of a multilayer and we try to reduce the Ta_2O_5 mechanical losses by doping the material and modifying some process parameters. We present also an analysis on the stress of the layers and we will show there is no relation between stress and loss.

2. Experimental procedure

Our measuring instrument was delivered at LMA by the INFN of Perugia in april 2004. The goal was to have a quick and low cost measurement of LMA coatings. Indeed before we have this bench we had to coat multilayers mirrors on three inches substrates and the measurements were made by MIT and IGR. This method was quite heavy and expensive and measurements were not possible for frequency around 100 Hz because of the substrates size.

With this bench we can realize studies at lower frequencies nearly 100 Hz for less expensive substrates but it allows also studies at higher modes. The bench (figure 2b) is laid on an antiseismic table to minimize the vibrations coming from the ground. The vacuum is ensured by a rough pump placed in another room to reduce the noise and by a turbo pump to reach a good vacuum: nearly 1.10-6 Torr.

Substrates are membranes of suprasil 311 silica coming from HERAEUS Company. This kind of silica is currently used for VIRGO and LIGO optics. The dimensions of the membranes are 45 mm long × 5 mm large and 110 µm thick. Substrates are cleaned up before coating in order to eliminate the surface impurities likely to disturb the measurement. They also undergo a long annealing before measurement which allows to accurate the eventual defects (cracks, dislocations due to the polishing).

Our technique consists in clamping an extremity of the membrane on 5 mm in a vice composed of two parts (figure 3). We have to clamp the membrane very tightly to minimize the dissipation contact losses. We noticed that the membrane breaks if we do not polish the surfaces of the vice in contact with it. Indeed we must have a contact surface very flat with a roughness as low as possible. So the two parts of the vice are polished together: surface contact and on the cross section to have a perfect square shape of the edges. Working on the vice and the polishing allows gaining a ratio 10 on the sensitivity measurement.

A good way to check the quality of our clamping is to compare the ratio between the frequencies modes. The frequencies can be calculated by[iv]

$$\nu(L,h) := \alpha^2 \cdot \frac{h \cdot \sqrt{\frac{E}{3\rho}}}{4 \cdot \pi \cdot L^2} \tag{2}$$

where L is the vibration length, h, ρ and E are respectively the thickness, the density and the Young Modulus of the membrane. In our experiment the length of vibration is 40 mm. α are coefficients for every mode: 1.875, 4.6941, 7.8547….When we compare the theoretical ratios to our experimental measurements we noticed they are very good which means our clamping system is nearly perfect (table 1).

One time the membrane mounted in the vice, we placed it into the inner experimental chamber of the bench (figure 2a). A He-Ne laser beam is reflected on the membrane which is electrically excited at the vibration frequency modes. Then the reflected beam is detected by a photodiode and the signal is analysed by the software developed under a labview environment. The typical signal we obtained is sinusoidal shape and we apply a Fourrier transform which gives us the amplitude of the vibration at the frequency mode studied (figure 4). The membrane vibrates freely and we noted an exponential decrease which gives us the mechanical losses of the membrane by the following formula:

$$A = A_0 e^{-\phi(\nu 0)\pi\nu 0t} \tag{3}$$

where A_0 is the initial amplitude of the motion, t is the time measurement, ν_0 is the frequency vibration and $Ø(\nu_0)$ are losses.

3. Calculation of the multilayer losses

Considering a system with a stack of layers deposited on a membrane, coating mechanical losses[v] can be expressed by the following formula.

$$\phi_{total}(f_0) = \phi_s(f_0) + \frac{Wc}{Ws}\phi_c(f_0) \tag{4}$$

where Φ_s are the substrate losses Φ_c the coating losses and Φ_{total} the total system losses. Ws/Wc is the ratio between the energy stored in the substrate and the energy stored in the coating. This ratio depends on the thickness and the Young modulus of the substrate and the coated material.

We developed an analytical model to calculate the mechanical losses in a multilayer principally to evaluate the ratio Ws/Wc primordial ratio for the calculation of the mechanical losses. This ratio was also calculated by finite element software with the same result.

The way of proceeding is the following: We measure the substrate losses and the losses after coating, we calculate the ratio Ws/Wc and finally we extract the coating losses. The ratio Ws/Wc can be easily expressed[vi] by

$$\frac{Ws}{Wc} = \frac{\int_0^{hs} (z - z_0)^2 \frac{Es}{1 - \nu_s^2} dz}{\int_{hs}^{hs+hc} (z - z_0)^2 \frac{Ec}{1 - \nu_c^2} dz} \tag{5}$$

where Es and ν_s are the Young modulus and Poisson coefficient of the substrate, Ec and ν_c are the Young modulus and Poisson coefficient of the coating, hs and hc are respectively the substrate and coating thicknesses and z_0 is the neutral axis (line where the sum of all the stress is equal to zero) defined by

$$\int_{0}^{hs+hc}(z-z_0).E(z).dz=0 \tag{6}$$

For a monolayer the expression of the neutral axis is simple:

$$z_0=\frac{1}{2}.\frac{Es.hs^2+Ec.hc.(2hs+hc)}{Es.hs+Ec.hc} \tag{7}$$

For a multilayer Ta_2O_5/SiO_2 the expression of z_0 is more complicated because we have to consider the Young Modulus and the Poisson coefficient of every layer. After a mathematic calculation we extracted a general expression for the neutral axis:

$$z_0=\frac{1}{2}.\frac{Es.hs^2+Ec1.hc1.(2hs+hc1)+\sum_{i=2}^{n}[Eci.hci.(2hs+hci+2.\sum_{k=1}^{i-1}hck)]}{Es.hs+\sum_{i=1}^{n}Eci.hci} \tag{8}$$

where Eci and hci are the young modulus and thickness of the i layer and n is the number of layers. For i strictly larger than one we obtained the following expression for the dissipated energy in all the coating:

$$Wc=\int_{hs}^{hs+hc1}(z-z_0)^2.\frac{Ec1}{1-(\nu c1)^2}dz+\sum_{i=2}^{n}\int_{hs+\sum_{k=1}^{i-1}hck}^{hs+\sum_{k=1}^{i}hck}(z-z_0)^2.\frac{Eci}{1-(\nu ci)^2}dz \tag{9}$$

One time the coating losses extracted we can compare to the theoretical prediction

$$\phi_c=\frac{Ec1.hc1}{Ec.hc}\phi_1+\frac{Ec2.hc2}{Ec.hc}\phi_2 \tag{10}$$

Φ_1 are the mechanical losses for tantala and Φ_2 are the silica losses, hc1 and hc2 are respectively the thicknesses of every layer and hc is the total coating thickness. In this equation Ec is the most difficult parameter to estimate because it is difficult to measure the young modulus of a multilayer. Nevertheless for a thin surface layer, the stress will be predominantly parallel to the surface and in this limit the total young modulus for the multilayer coating can be approximated by:

$$Ec.hc = Ec1.hc1 + Ec2.hc2 \tag{11}$$

It is a linear combination of young modulus of every material. The Ta_2O_5 and SiO_2 Young modulus are respectively 141 and 72.7 GPa. For a quarter waves mirror centred at 1064 nm the Ta_2O_5 layer thickness is 130 nm and the SiO_2 layer thickness is 182 nm.

4. Reduction of mechanical losses

First of all an important point we wanted to check is the homogeneity of the losses on the whole surface mirror. In our large coater the diameter of the substrate holder is 350 mm, size of Virgo optics mirrors. We placed in the same run a membrane on the edge and a membrane in the center of the substrate holder. After coating and annealing we measured the two membranes losses:

$Ø_{Ta2O5}=3.02.10^{-4}$ +/- $0.1.10^{-4}$ (center)

$Ø_{Ta2O5}=2.96.10^{-4}$ +/- $0.01.10^{-4}$ (edge)

We noticed that the two values are the same which means that the coated material is quite homogeneous. In a second time we decided to prove that our coatings and measurements for Ta_2O_5 and SiO_2 were very reproducible (Table 2).

Secondly we interested in the reduction of the thermal noise. If we directly apply the Fluctuation-Dissipation Theorem for a Gaussian profile laser the thermal noise can be expressed by[vii]

$$S_X(f) = \frac{2k_B T\,(1-\sigma^2)}{\pi^3.w.f.E}\phi_{eff} \qquad (12)$$

where σ is the Poisson coefficient of the substrate, w is the half-width of the Gaussian laser beam and $Ø_{eff}$ are the losses mirror. When we look at this expression we see three different ways to reduce the thermal noise. The first consists in reducing the measurement temperature T, which is planed for the future generation of cryogenic interferometric detectors (LIGO and LCGT in Japan).

The second way is to modify the laser beam Gaussian profile to obtain flat (mesa) beam[viii] in accordance with the realisation of non spherical mirrors to support it. One will also have a more homogeneous distribution of the local heating. The mirrors are called Mexican Hat and are realized using a corrective coating developed in our lab to be able to coat on specific point of the mirror. With the Mexican hat and the flat (mesa) beam it is possible to reduce significantly the thermal noise.

The final way is to reduce the system mechanical losses. In the expression of the thermal noise $Ø_{eff}$ is the sum of the substrate and coating losses but we know the coating losses are very important compare to substrate losses. So we work on this point.

4.1. Doping Influence

Ta_2O_5 mechanical losses being predominant in Ta_2O_5/SiO_2 coatings, we investigated several ways to reduce these losses by doping the layer (table 2). Doping with Cobalt or Tungsten was not interesting as well for optical properties as for mechanical losses. When we compare the W+Ti doped tantala to the Ti doped tantala we can see that the absorption is similar in both cases. Although mechanical losses are better with W+Ti doping for a single layer, this doping is not interesting. When we realize a W+Ti doped Ta_2O_5/SiO_2 mirror the absorption considerably increases whereas with Ti doping the absorption of the mirror is lower than 1 ppm. We suppose for the W+Ti doping there is Tungsten diffusion through the different layers.

After several attempts (different concentrations of Ti doping) Formula 5 is actually the best result we obtained with Ti doping. It corresponds to an incorporation of 14.5 % of Ti in the tantala layer. With this formula we succeeded in reducing the tantala losses by 17%.

4.2. *Influence process parameters*

A lot of process parameters take place during the deposition and are responsible of the number of ions which will sputter the target, of their energies and acceleration. We must also control the oxygen partial pressure used to oxide the material and obtain the good stoechiometry and the temperature of the substrate. We assumed that some parameters could have an influence on mechanical losses of the material. To confirm this assumption we modified some of them.

But for confidentiality reasons we can not describe in detail the process used, so we have called X this parameters changing. Modifying this X parameter by 17% we observed a reduction of nearly 10 % of the formula 5 mechanical losses (table 3). So we decided to double the modification of X and we reduced again the losses. Unfortunately we could not modify this X parameter beyond 35 % without changing the optical properties of the material. Finally we succeeded in reducing of more than 30% the tantala losses.

4.3. *Optimized Coatings*

Another way to reduce the coating mechanical losses is to modify the geometry of the mirrors coatings optimizing the design[ix]. We know the tantala is highly responsible in final coating mechanical losses, so we assumed by reducing the tantala total thickness we would reduce the total coating mechanical losses and consequently the thermal noise. From the equation 13 the coating thermal noise power spectral density can be approximated by

$$S_X(f) = C(h_H + \gamma^{-1}.h_L) \tag{14}$$

where h_H and h_L are respectively the total thicknesses of the high and low index coating materials. C is a constant and γ is the ratio between Φ_H and Φ_L mechanical losses of the high and low index materials. It can be expressed by

$$\gamma \approx \frac{E_H.\phi_H.n_H}{E_L.\phi_L.n_L} \tag{15}$$

with n_H and n_L the materials optical indexes. Some simulations have been realized at the University of Sannio and in our lab to reduce the tantala total thickness without modifying the optical properties of the coating. Table 5 compares the thicknesses of a quarter wave coating to an optimized coating (genetic prototype). An optimized coating with Ti-doped Ta_2O_5 will allow a 25% event rate boost at 100 Hz compared to a quarter wave coating (for a value of $\gamma \sim 10$).

4.4. Relationship between stress and losses

A point which seemed us to be interesting is to try to find a correlation between the stress and the losses in the layers. For every membrane we have measured the stress and the mechanical losses before and after annealing for SiO_2 and Ta_2O_5 layers. We noticed (figure 5) that a low stressed coating is not necessarily a low mechanical losses coating. We clearly see the tantala layers are more stressed after annealing although the mechanical losses are reduced.

5. Conclusion and future work

The influence of the doping is essential to reduce the mechanical losses in the tantala layers so we reduce the ratio 6 to 4 between the tantala and silica losses. We showed by modifying some process parameters we can reduce the tantala mechanical losses. We also put in evidence that for our coatings of silica and tantala there is no relation between a low stressed coating and a low mechanical losses coating. With our theoretical model we can now calculate the mechanical losses for multilayer coatings.

Regarding the expression of the thermal noise, another way is envisaging for the reduction of the coating losses with the realisation of Mexican Hat using a corrective coating for flat top mesa beam.

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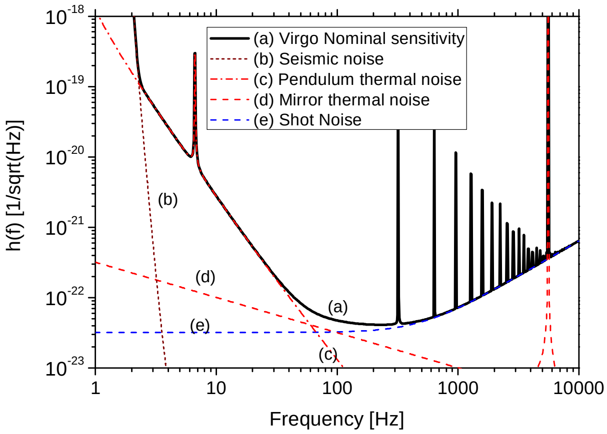


Figure 1. Illustration of different noise source for the gravitational detection

a) **b)**

Figure 2. Membrane clamped in the vice inside the inner experimental chamber (a). Detection of the reflected beam (b)

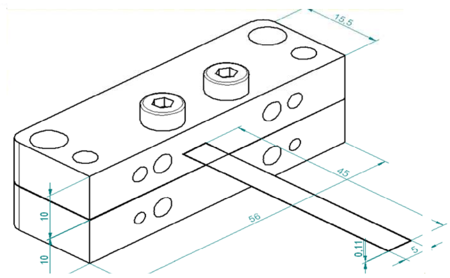
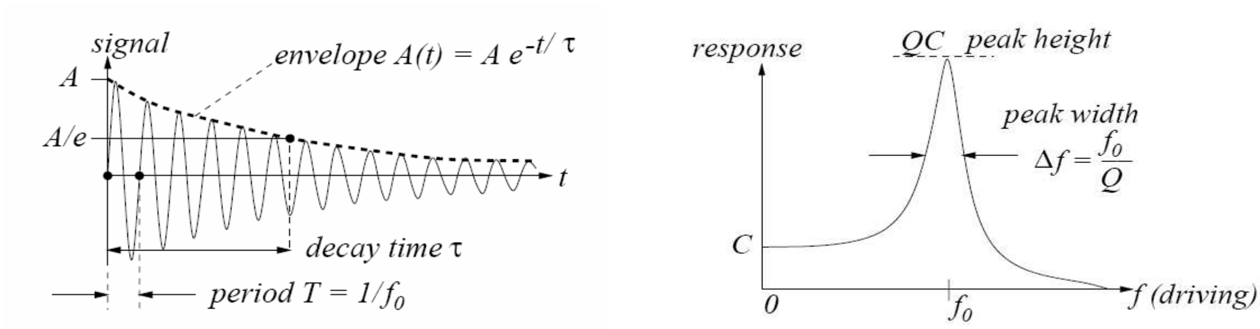


Figure 3. Membrane clamped in the vice



a) **b)**

Figure 4. Exponential decrease of the membrane (a). Fourier transform which give us the frequency vibration of the membrane (b).

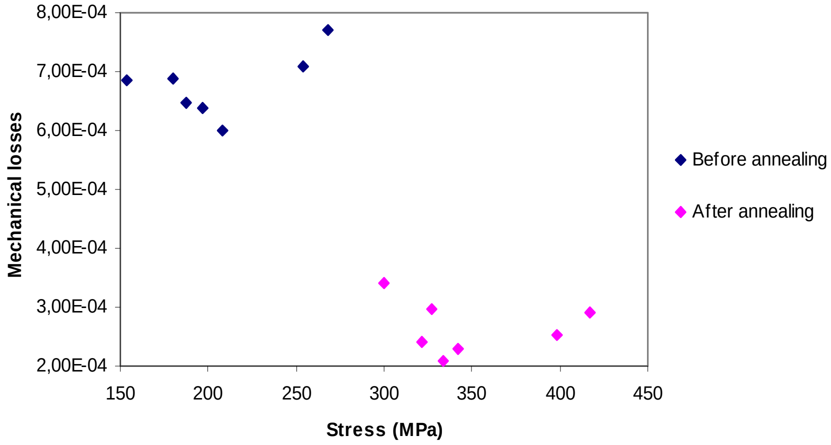


Figure 5. Ta_2O_5 mechanical losses and stress before and after annealing

Table 1
Comparison between the ratios of the frequency modes

Theoretical ratios	Measured ratios
$\nu_2 / \nu_1 = 6.2677$	$\nu_2 / \nu_1 = 6.252$
$\nu_3 / \nu_2 = 17.547$	$\nu_3 / \nu_2 = 17.5$

Table 2
Mechanical losses and optical properties for Ta_2O_5 and SiO_2

Layer *	**Losses ****	**n**	**k (1064 nm)**
Ta_2O_5	$3.\ 10^{-4}$	2,015	6,97 E-07
	$2.96.\ 10^{-4}$	"	"
	$3.01.\ 10^{-4}$	2,02	1,96 E-07
SiO_2	$> 5.5.\ 10^{-5}$	1,458	3,6 E-08
	$4.47.\ 10^{-5}$	1,458	3,6 E-08

* The thickness of the coating is 0.5 µm
** Measurement after annealing

Table 3
Mechanical losses and optical properties for doped-Ta_2O_5

Coating *	**Doping**	**Absorption (ppm)**	**Mechanical losses**
Ta_2O_5	/	1.22	3. E-04
	Co	5 000 !	1.1. E-04
	W	2.45	7.5. E-04
	W+Ti	1.65	1.85. E-04
		> 50 **	No measured
	Ti	1.7	2.43. E-04
		0.89 **	No measured

* The thickness of the coating is 0.5 µm
** for a $(HL)_{15}HLL$ mirror

Table 4

Mechanical losses for Ti-doped Ta_2O_5 with X parameter modification

Coating *	**X parameter reduction**	**Mechanical losses**
Ti-Doped-Ta_2O_5	/	2.43. E-04
	17 %	2.2. E-04
	35 %	2. E-04

* The thickness of the coating is 0.5 µm

Table 5

Thicknesses comparison between a Ta_2O_5/SiO_2 quarter wave and a Ta_2O_5/SiO_2 optimized coating; layers counted from substrate interface ; first layer is Ta_2O_5

Quarter wave coating $(HL)_{17}HLL$	Optimized coating $(HLL)_{22}$
130.71	85.6212504
182.7	246.894816
130.71	85.9794991
182.7	246.345792
130.71	82.5627824
182.7	238.1764
130.71	86.2679496
182.7	244.990256
130.71	80.5266056
182.7	263.268712
130.71	81.1121248
182.7	226.01488
130.71	78.3069952
182.7	247.701328
130.71	83.1307456
182.7	261.290736
130.71	82.4491472
182.7	208.651464
130.71	86.1368648
182.7	267.774752
130.71	83.6725344
182.7	259.97244
130.71	80.4129703
182.7	269.972976
130.71	78.12134552
182.7	232.719144
130.71	84.872572
182.7	280.11928
130.71	64.797068
182.7	256.895352
130.71	87.0806328
182.7	215.978168
130.71	84.6862072
182.7	259.6426
130.71	77.616672
182.7	253.965096
182.7	85.49889
	246.41920
	86.643648
	247.48108
	86.582468
	231.290192
	83.8297935

	11.838928
Total thickness SiO_2 : 3471.3nm	Total thickness SiO_2 : 5217 nm
Total thickness Ta_2O_5 : 2352.78 nm	Total thickness Ta_2O_5 : 1816 nm
Total thickness coating : 5824.08 nm	Total thickness coating : 7033 nm

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